Turbine Design I

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Outline

- Basic turbine designs
- Turbine loads and blades
- Design for noise
- Design trade-offs

Wind Turbines

Wind Farm

Wind Turbine

Turbine Classification: Axis Direction

- Horizontal axis
- Vertical axis
New Design Example: WindCube

- Small in size compared to the standard horizontal WT
- Designed for roof placement in urban and rural areas
- Power amplification
- 22 x 22 x 12 feet in size, 60kW output
- Cut-in speed 5m/h
- Annual power of 160,000 kWh at average wind speed of 15 mph

Equivalent to 50 feet diameter horizontal WT rotor

Examples: Residential WT

Southwest Windpower http://www.windenergy.com
WindTamer™ Turbine

http://www.awrwinds.com/

Residential WT

Eldridge (1980)

Vertical Axis Turbines

WRE 007
750 W

WRE 030
3,000 W

WRE 060
6,000 W

Wind Turbine History

Errichello and Muller, Geartech

Darrieus wind turbines
Wind Turbine History

Offshore wind turbines near Copenhagen

Upwind turbines
➤ Rotor is facing the wind

Downwind turbines
➤ Rotor placed on the lee side of the tower

Wind-Rotor Position

Why Horizontal Axis WT?

Tips speed

Power coefficient

Mathew (2006)

Mathew (2006), p. 22

Tip speed ratio (TSR)

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Turbine Components

Operating Principles of Wind Turbines

The wind passes over both surfaces of the airfoil shaped blade. It passes more rapidly over the longer (upper) side of the airfoil, creating a lower-pressure area above the airfoil. The pressure differential between top and bottom surfaces results in a force, called aerodynamic lift.

In an aircraft wing, this force causes the airfoil to "rise," lifting the aircraft off the ground. Since the blades of a wind turbine are constrained to move in a plane with the hub as its center, the lift force causes rotation about the hub. In addition to lift force, a "drag" force perpendicular to the lift force impedes the rotor rotation. A prime objective in wind turbine design is for the blade to have a relatively high lift-to-drag ratio. This ratio can be varied along the length of the blade to optimize the turbine’s energy output at various wind speeds.

WT Major Components

Sterzinger and Storcik, NREP, 2004
Turbine Structure

Hub

Gearless Turbine

Power Flow Concept

Blaabjerg and Chen (2006)

http://www.richterag.de/english/highlights/windkraftanlage

Enercon

http://www.world-wind-energy.info/

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http://www.world-wind-energy.info/
Upwind Turbines

Advantages:
- Upwind designs **avoid the wind shade** behind the tower as it faces the wind
- The **vast majority** of wind turbines have this design

Disadvantages:
- The basic drawback of upwind designs is that the rotor needs to be rather inflexible, and placed at some distance from the tower (at an increased cost)
- A **yaw mechanism** needed to keep the rotor facing the wind
- Some wind shade in front of the tower gets created, i.e., the wind bends away from the tower before it reaches the tower itself. Each time the rotor passes the tower, the power from the wind turbine minimally affected

Downwind Turbines

Advantages:
- They can be built **without a yaw mechanism**, if the rotor and nacelle are designed so that the nacelle follow passively the wind
- The rotor can be made **more flexible**. This helps structural dynamics and it reduces turbine weight, i.e., thinner blades bend, thus taking part of the load off the tower

Disadvantages:
- The basic drawback is the **fluctuation in the wind power** due to the rotor passing through the wind shade of the tower
- **Larger fatigue loads** on the turbine than with an upwind design

Turbine Classes

Four basic classes defined by the wind speed and turbulence data. The wind data is characterized by:
- the **maximum wind speed** to be expected as a mean value over 10 min, the so-called reference wind velocity ($v_{ref}$)
- the **mean annual wind speed** ($\overline{v}$)
- the **turbulence intensity** at a wind speed of 15 m/s ($I_{15}$)

Within the four classes, the two categories A and B characterize the design for different turbulence conditions:
- The standard deviation ($\sigma_1$) of the longitudinal wind velocity (turbulence) is specified by the parameter $a$

Turbine Classes

<table>
<thead>
<tr>
<th>WT Classes</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{ref}$ (m/s)</td>
<td>50</td>
<td>42.5</td>
<td>37.5</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>$\bar{v}$ (m/s)</td>
<td>10</td>
<td>8.5</td>
<td>7.5</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>$v_{G50} = 1.4v_{ref}$</td>
<td>70</td>
<td>59.5</td>
<td>53.5</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>$v_{G1} = 1.05v_{G50}$</td>
<td>52.5</td>
<td>44.6</td>
<td>39.4</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>A $I_G$</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>B $I_G$</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>


Turbulence Intensity $I$

$$I_t = \frac{\sigma}{\bar{v}_t}$$

$$\sigma_t = \frac{1}{a-1} \sum_{i=2}^{a} (\text{var}_i - \text{var})$$

$$\text{var}_i = \frac{1}{n_{\text{var}_i}} \sum f(i)$$

$\sigma_t$ is the standard deviation of the wind speed variation about the mean wind speed $\bar{v}_t$ at time $t$.

$\bar{v}_t$ is the mean wind speed over a certain interval at time $t$.

Blades

- Due to stability, modern wind turbines are designed with an odd number of rotor blades.
- When the uppermost blade bends backwards while getting the maximum power from the wind, the lowermost blade passes into the wind shade in front of the tower.
Blade Sizes

Examples:

- TPI: Newton, IA (Impregnated TYCOR – sponge type material)
  - 37m for GE 1.5MW turbine (manufactured)
  - 48.7m for GE 2.5 MW turbine (to be manufactured)

- Siemens: Ft Madison, IA (patented single piece casting of epoxy raisins)
  - 45m for 2.5MW turbine
  - 52m for 3.6MW turbine (sea-based applications, outside of US)

Blade Manufacturing

Basic manufacturing steps (TPI Corp):

- Infusion (reusable silicon bag technology)
- Demolding
- Assembly
- Inspection
- Transportation

Manufacturing challenge:

- Cost reduction

Energy challenge:

- Low energy manufacturing processes and optimized transport

Blade Transportation

Transportation cost

- Up to 25% of the blade cost

Blade packaging for transportation:

- Smaller blades, e.g., < 27 m (3 blades per truck)
- Medium size (2 blades per truck)
- Large blades (1 blade per truck)

Blade Sizes

<table>
<thead>
<tr>
<th>Turbine power</th>
<th>Blade length</th>
</tr>
</thead>
<tbody>
<tr>
<td>7MW blade</td>
<td>~75m</td>
</tr>
<tr>
<td>5MW blade</td>
<td>~65m</td>
</tr>
<tr>
<td>3.6MW blade</td>
<td>~55m</td>
</tr>
<tr>
<td>1.5MW blade</td>
<td>~40m</td>
</tr>
<tr>
<td>.75MW blade</td>
<td>~25m</td>
</tr>
<tr>
<td>.5MW blade</td>
<td>~20m</td>
</tr>
<tr>
<td>.1MW blade</td>
<td>~10m</td>
</tr>
</tbody>
</table>
Blade Design Challenge

Cost: Existing technology/expertise does not generally transfer

<table>
<thead>
<tr>
<th>Application</th>
<th>Cost</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-end military</td>
<td>~$1,000/lb</td>
<td>$10^6</td>
</tr>
<tr>
<td>Aerospace applications</td>
<td>~$100/lb</td>
<td>$10^6</td>
</tr>
<tr>
<td>Wind-turbine blade</td>
<td>~$&lt;10/lb</td>
<td>$10^8</td>
</tr>
</tbody>
</table>

Example

Performance: Shape, materials, sensors (e.g., accelerometers) for active blade control

Weight: e.g., use of carbon fiber

Blade Design for Reliability

Design requirement: Failure probability $p$ less than $10^{-5}$

Number of Blades

<table>
<thead>
<tr>
<th>Design Concept</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-blade design concept</td>
<td>- Most popular</td>
</tr>
<tr>
<td>Two-blade design concept</td>
<td>- Lower cost and weight</td>
</tr>
<tr>
<td></td>
<td>- Higher rotational speed</td>
</tr>
<tr>
<td></td>
<td>- Hinged rotor that tilts to avoid heavy shocks to the turbine when a rotor blades passes the tower</td>
</tr>
<tr>
<td>Single-blade design concept</td>
<td>- A counterweight is required to balance the rotor</td>
</tr>
</tbody>
</table>

Turbine Noise

Sources of turbine noise:

- Aerodynamic
  - Turbine rotor (blades) is the main source
- Mechanical
  - Rotating parts, e.g., gears
Sources of Aerodynamic Noise

- Wind hitting an object generates a sound
- It may also set surfaces in vibration
- Turbine blades brake the wind to transfer its energy to the rotor thus emitting some white noise
- Sound pressure increases with the fifth power of the speed of the blade relative to the surrounding air
- Additive sound effect of multiple turbines

Design for Aerodynamic Noise

- Surfaces of the rotor blades must be smooth
  (Noise and aerodynamic reasons)
- Design of trailing edges key to sound reduction
- Different tip designs of blades (complex flow + largest speed)
- Low rotor speed
- Careful handling of rotor blades and maintenance

Design for Aerodynamic Noise

- Noise not a problem today
- Human perception versus reality
- The noise from the wind passing leaves, shrubs, trees, masts, etc essentially masks sound from wind turbines operating at winds speeds around 4 - 7 m/s and up
- Sound maps

Examples of sound levels

<table>
<thead>
<tr>
<th>Sound Level</th>
<th>Threshold of Hearing</th>
<th>Whisper</th>
<th>Talking</th>
<th>City Traffic</th>
<th>Rock Concert</th>
<th>Jet Engine 10 m Away</th>
</tr>
</thead>
<tbody>
<tr>
<td>dBA [A]</td>
<td>0</td>
<td>30</td>
<td>60</td>
<td>90</td>
<td>120</td>
<td>150</td>
</tr>
</tbody>
</table>

A = absolute scale

Design for Noise

Sound propagation and distance: Inverse square law

\[ I = \frac{P}{4\pi r^2} \]

The noise level \( I \) in an inverse square of the distance \( r \), where \( P \) = power at source

- At one rotor diameter distance (e.g., 43 m) from the base of a wind turbine emitting 100 dB(A) the sound level is 55-60 dB(A).
- 4 rotor diameters (170 m) away the level is 44 dB(A).
- 6 rotor diameters (260 m) away the level is 40 dB(A).

Example: Sound propagation and distance

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Design for Noise

Sources of Mechanical Noise

- Metal components moving or knocking against each other generate noise (e.g., gearbox, drive train shaft, turbine generator)
**Gearbox Design for Noise**

- Shift from industrial gearboxes to turbine specific gearboxes
- Steel wheels of the gearbox have a semi-soft, flexible core, and hard surface to ensure strength and long time wear
- Accomplished by heating gear wheels after the teeth have been ground, and then cooling them off slowly while they are packed in a special high carbon-content powder
- The carbon will then migrate into the surface of the metal
- This ensures a high carbon content and high durability in the surface of the metal, while the steel alloy in the interior remains softer and more flexible

**Vibration Noise**

**Remedy**

- Structural dynamics analysis to avoid vibration
- For example, holes drilled in a nacelle to avoid vibration
- Sound insulation rarely used today, although to reduce some medium- and high-frequency noise it could be applied

**Turbine Electromagnetic Interference**

- A concern to radar installations

**Shadow Flicker and Flushing**

- Moving rotor may cast shadow or sunlight reflections may cause a flushing effect, both causing annoyance
Turbine Design Trade-offs

Victoria in Southern Australia would never have been populated in the late 19th century, were it not for the water pumping windmills - and these windmills were actually optimized for the purpose they served.

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Turbine Design Trade-offs

- An ideal wind turbine design is not dictated by technology alone, but by a tradeoff between technology and costs.
- Turbine designs are optimized to deliver electricity at the lowest possible cost per kilowatt hour (kWh).
- The manufacturers are not very concerned with the efficiency of use the wind resource as the fuel is free.
- Maximizing the annual energy production is not the primary design objective to avoid excessive costs of turbines.

Acknowledgement

The material included in the presentation comes largely from the Danish Wind Industry Association.

Generator vs Rotor Size

- A small generator, i.e., a generator with low rated power output in kW, requires less force to turn than a large one.
- A large wind turbine rotor powering a small generator produces electricity for many hours of the year, however it captures only a small portion of the energy content of the wind at high speeds.
- A large generator, on the other hand, is very efficient at high wind speeds, but unable to turn at low wind speeds.